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Indoor Environmental Quality in Six Commercial Office Buildings in the Midwest United States

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The aims of this study were to characterize physical, mechanical, and environmental factors influencing indoor environmental quality (IEQ) in commercial office buildings; document occupant perceptions and psychosocial attributes; and evaluate relationships among these parameters. Six large office buildings in metropolitan areas were selected in Iowa, Minnesota, and Nebraska. Comprehensive sampling was conducted over one week in each building, during all four seasons. This paper presents the study methods and selected results from the first round of sampling (November 1996 to April 1997). Air flow and recirculation rates were quite variable, with the proportion of outdoor air provided to occupants ranging from 10 to 79 CFM/person. Carbon dioxide, carbon monoxide, and temperature were within ranges anticipated for nonproblem buildings. Relative humidity was low, ranging from 11.7 to 24.0 percent. Indoor geometric mean concentrations of total volatile organic compounds (TVOCs) ranged from 73 to 235 $\mu g/m^3$. The most prevalent compounds included xylene, toluene, 2-propanol, limonene, and heptane. Geometric mean formaldehyde concentrations ranged from 1.7 to 13.3 $\mu g/m^3$, and mean acetaldehyde levels ranged from <3.0 to 7.5 $\mu g/m^3$. Airborne concentrations of culturable bacteria and fungi were low, with no samples exceeding 150 CFU/m^3. Total (direct count) bioaerosols were more variable, ranging from 5010 to 10,700 organisms/m^3. Geometric mean endotoxin concentrations ranged from 0.5 to 3.0 EU/m^3. Respirable particulates (PM10) were low (14 to 36 $\mu g/m^3$). Noise levels ranged from 48 to 56 dBA, with mean light values ranging from 200 to 420 lux. Environmental parameters were significantly correlated with each other. The prevalence of upper respiratory symptoms (dry eyes, runny nose), central nervous system symptoms (headache, irritability), and musculoskeletal symptoms (pain/stiffness in shoulders/neck) were elevated compared to other studies using similar questionnaires. Importantly, psychosocial factors were significantly related to increased symptoms in females, while environmental factors were more closely correlated with symptoms in males. Endotoxin concentrations were associated with symptoms in both males and females. These data will help to identify and quantify the relative role of factors that contribute to sick building syndrome. The data collected in this study may also be used to evaluate the effectiveness of current building operation practices, and can be used to prioritize allocations of resources for reduction of risk associated with IEQ complaints.

Indoor Environmental Quality (IEQ) is an important public health issue. It includes widely publicized problems such as sick building syndrome, building-related illness, and multiple chemical sensitivity. IEQ problems are estimated to effect more than 10 million workers in up to 30 percent of buildings in the United States alone, resulting in billions of dollars of decreased productivity, litigation, and adverse publicity.[1,2]

Multiple chemical sensitivity (MCS) is quite controversial and can be difficult for buildings' operators to resolve. Building-related illnesses (BRI), where specific causal agents such as *Legionella* bacteria can be identified, are often easier to explain and resolve. Sick Building Syndrome (SBS), characterized by subjective responses to nonspecific conditions continues to present a significant challenge. Although extensive resources have been devoted to the investigation of indoor environmental quality problems over the last two decades, a complete

understanding of the factors involved remains elusive. Causal factors (when identified) include primarily mechanical ventilation systems and air conditioning, microbiological agents, and chemical agents.[3–6] Physical parameters such as lighting, noise, temperature, and humidity have also been implicated.[7] The potential contribution of psychosocial factors has been addressed by several authors.[8–10] The multifactorial nature of SBS is particularly apparent in the extreme situations where buildings have been evacuated (i.e., crisis buildings).[11]

Although there is extensive literature concerning indoor environmental quality, there remain significant gaps in our understanding of its causes, and methods for preventing or controlling SBS. This is partly due to the lack of experimental evaluations using standardized methodologies, as opposed to the nonstandardized reactive investigations of problem buildings. A few recent IEQ studies used a standardized protocol and questionnaire, the New Standard Environmental Inventory by the Air Pollution Control Association, with subsequent editions from the National Institute for Occupational Safety and Health (NIOSH) and the U.S. Environmental Protection Agency (EPA).[12–15] As part of their Health Hazard Evaluation Program, NIOSH used this instrument to survey 105 problem buildings.[15] Cole also used this instrument to evaluate five problem buildings, while Nelson utilized it to characterize four nonproblem buildings in Washington.[13,14]

The EPA has developed a national database for nonproblem buildings using this NIOSH/EPA questionnaire as part of their standardized Building Assessment Survey and Evaluation (BASE) project.[16] Our study used EPA's BASE protocol, with additional environmental and questionnaire aspects, to evaluate baseline conditions in large commercial buildings in the midwestern United States, and to study the relationships between environmental factors, mechanical conditions, psychosocial characteristics, and symptoms reported by workers employed in these buildings. Six buildings were selected for the study, with each building visited for a period of one week during each of the four seasons.

The goals of this study included collection of baseline data to quantify and characterize the following:

- The physical, mechanical, and environmental factors that influence IEQ in six nonproblem buildings in the midwestern United States
- Human exposures to particles, microorganisms, volatile organic compounds, formaldehyde, acetaldehyde, carbon dioxide, carbon monoxide, temperature, relative humidity, noise, and light
- Occupant perceptions of IEQ and psychosocial attributes of the workgroups

Preliminary results on selected aspects of this project were published previously.[17–19] This paper comprehensively presents the methods used for this study and summarizes results from the first round of sampling in each building (November 1996 to April 1997).

METHODS

Selection of Buildings, Test Spaces, and Sampling Locations

Six commercial office buildings in the midwestern United States were selected from among 20 potential available buildings owned and operated by one corporation. The following criteria were used: the building had to be located in a large metropolitan area; occupied by more than 100 employees; and within the region including Iowa, Nebraska, and Minnesota. Buildings with significant or publicized complaints related to IEQ were excluded from this study. Test spaces were selected in each building according to the procedure specified in the EPA document, *A Standardized Protocol for Characterizing Indoor Air Quality in Large Office Buildings,* Section 3.0, pages 3-1 to 3-3.[16] Test spaces had to be served by no more than two air-handling systems, contain at least fifty occupants, and could not share common ventilation with cafeterias, storage rooms, or mechanical rooms. Sample sites within each test space were randomly selected using a grid system and a formula accounting for the number of possible sites. Three "fixed" monitoring locations were selected in each test space. Integrated, continuous, and real-time monitoring were conducted at the fixed sites. Five additional "mobile" monitoring sites were also selected. Only limited direct reading measurements were recorded at these locations. One outdoor sample site was also selected in each building. It was located as close as possible to the outdoor air intake for the primary air-handling system for the study area. If not already sheltered, a temporary shelter was constructed to protect sampling equipment from the elements. Samples collected outside included the same parameters sampled at fixed locations inside. Measurement of volumetric air flow, temperature, relative humidity, carbon dioxide, and carbon monoxide were made in the intake, supply, and return components of the test space air-handling systems.

Sampling Schedule

Measurement of supply air flow to the test space was conducted first. Direct reading measurement of gases and comfort parameters (carbon dioxide, carbon monoxide, temperature, relative humidity, noise, light) was performed at fixed stations and the outdoor station (excluding noise and light measurements) on three consecutive days (Tuesday, Wednesday, and Thursday). Duplicate samples were collected at one fixed station indoors and at the outdoor station. Air-handling system measurements were also conducted over the same three days. Integrated sampling for volatile organic compounds (VOCs), aldehydes, the PM10 particulate fraction, endotoxin, and direct count microbials was conducted at the fixed stations and outdoors on Wednesdays. Culturable microbials were also sampled in the morning and afternoon of each Wednesday, and bulk microbial samples were collected from potential sources. Questionnaires were completed by test space occupants on Thursday and Friday.

Evaluation of Building Design and Operation

The type of building design and air-handling system were characterized using the procedures and checklists in the EPA's *A Standardized Protocol for Indoor Air Quality in Large Office Buildings.*[16] Data collected included information on the structural characteristics of each building and test space; the type and condition of air-handling systems; operational characteristics of the air-handling systems; maintenance and inspections; and potential sources of contaminants near the building. Data were entered into the EPA's Indoor Air Data Collection System (IADCS) program.

Ventilation

Volumetric air flow was measured in supply, return, and intake ducts using a pitot tube and a direct reading instrument—Velocicalc (TSI Inc., St Paul, MN) to determine velocity pressure. Measurements were made according to the protocols of ANSI/ASHRAE Standard 111-1988.[20] The number and specific location of measuring points within the duct depended on the size and shape of the duct. Because the supply duct was not accessible in one building, a tachometer was used to measure fan rotation speed and static pressure was measured; a fan table obtained from the fan manufacturer was used to calculate volumetric flow. A direct reading device, Q-Trak model 8551 (TSI Inc., St Paul, MN), was used to measure temperature, relative humidity, carbon monoxide, and carbon dioxide inside air-handling systems. A direct reading flow hood, Accubalance (TSI Inc., St Paul, MN) with variably configured hoods, was used to measure air flow from supply diffusers in the test space.

Sampling and Analysis of Environmental Parameters

Gases and Comfort Parameters

Temperature was monitored continuously at four elevations (10, 60, 110, and 168 cm above the floor) at each fixed station, and at one level for the outdoor station, using thermocouple wires and Rustrak Scout data loggers (Gulton-Rustrak, East Greenwich, RI). Data were downloaded to a laptop computer at the end of each day using Rustrak Ranger software version 3.61 (Gulton-Rustrak, East Greenwich, RI). Temperature was also recorded continuously at each fixed station and outdoors using direct reading devices—Q-Trak Model 8551 (TSI Inc., St Paul, MN). These instruments also recorded relative humidity, carbon monoxide, and carbon dioxide. Carbon dioxide was measured using nondispersive infrared (NDIR) detectors, while carbon monoxide was detected using electrochemical sensors. Data were recorded every five minutes throughout the day, and downloaded into a laptop computer at the end of each day using TrakPro Data Analysis Software version 2.11 (TSI Inc., St Paul, MN). Temperature probes were calibrated daily using a dry bulb thermometer, and a sling psychrometer was used to field calibrate relative humidity sensors. Standard gases were used for calibration of carbon monoxide and carbon dioxide sensors.

Volatile Organic Chemicals (VOCs)

VOCs were sampled and analyzed using EPA Method TO-1.[21] Air samples were collected on tenax in stainless steel tubes (Supelco, Bellefonte, PA) using calibrated vacuum pumps (MSA Inc., Eighty Four, PA) with twin port adapters at a flow rate of 50 ml/min. Samples were sealed in a container with an activated carbon bed and stored on ice for shipping to the laboratory. Samples were loaded with internal standards in the laboratory and analyzed by GC-MS after thermal desorption and cryofocusing. In addition to the target compounds specified in method TO-1, other significant peaks were identified and quantified to the degree possible. In addition to individual peaks, total VOC concentrations were calculated relative to the standard mass of toluene (TVOCs as toluene).

Formaldehyde and Acetaldehyde

Formaldehyde was sampled and analyzed using EPA Method TO-11.[21] Samples were collected using 2,4-dinitrophenylhydrazine (DNPH)-coated silica gel cartridges (Supelco, Bellefonte, PA) and the same twin-port-adapted vacuum pumps used for VOCs, calibrated at a flow rate of 200 ml/min. Samples were analyzed as the respective hydrazine derivative on reverse phase C-18 cartridges using an HPLC, with UV-VIS detector at 360 nm.

Culturable Bioaerosols

Culturable bacteria and fungi were sampled according to standard methods and the *Guidelines for the Assessment of Bioaerosols in the Indoor Environment* (ACGIH, 1989).[25] A total of 12 samples were taken at each fixed and outdoor station. Four air samples each for culturable mesophilic bacteria, thermophilic bacteria, and fungi were collected. Samples were taken once during the morning and once during the afternoon each Wednesday using Andersen N-6 Single Stage Microbial Samplers (Graseby Andersen, Smyrna, GA) containing selective media. One sample was collected for two minutes and one for five minutes at each location for each medium using a flow rate of 28.3 Lpm. Selective media used included Trypticase Soy Agar (TSA) with cycloheximide for mesophilic and thermophilic bacteria, and Malt Extract Agar (MEA) with chloramphenicol for fungi. Mesophilic bacteria were incubated at 32°C, thermophilic bacteria were incubated at 55°C, and fungi were incubated at 25°C and counted daily for at least 5 days. The number of colonies growing was counted, and Positive Hole Correction factors applied to calculate airborne concentrations in colony forming units per cubic meter of air (CFU/m^3). Microscopic examination and comparison to standardized keys were used to identify fungi by genus. Gram staining was used to categorize bacteria.

Microbiological Source Samples

Bulk samples for bacteria and fungi were collected from potential sources including drip pans, humidifiers, linings of HVAC plenums and ducts, and from carpet near the fixed indoor sites according to the procedures outlined in the EPA BASE protocol and the *Guidelines for the Assessment of Bioaerosols*

in the Indoor Environment.[16,25] One square meter of carpet at each of the three fixed stations was vacuumed into a composite sample using a Dust Devil handheld vacuum (Black & Decker, Hampstead, MD). Two passes of the entire surface were made, with the second pass at a right angle to the first. Sterile swabs wetted with sterile water were used to collect surface samples from defined areas on drip pans (not containing liquid), cooling coils, and other hard surfaces. Sterile pipettes were used to collect samples from sources containing liquids (such as drip pans). Sterile scissors or scalpels were used to cut pieces of filter or lining in HVAC plenums and ducts. Samples were collected in sterile containers and stored in insulated containers on ice for shipping. Samples were processed and plated onto selective media (as above) in the laboratory. The number of colonies growing was counted, and results reported as CFU/ml for liquid samples and CFU/g for bulk solids. Microscopic examination and comparison to standardized keys was used to identify fungi by genus; Gram staining was used to categorize bacteria.

Endotoxins

Airborne endotoxins were collected using pre-weighed 37 mm (binder-free) glass fiber filters (Gelman Scientific, St. Louis, MO) and vacuum pumps (Sensidyne, Miami, FL) at flows of 2.0 Lpm. They were analyzed using a Chromogenic end point Limulus Amoebocyte Lysate Assay as described by Reynolds and Milton, and Thorne, Reynolds, Milton et al.[22,23] Samples were stored with desiccant immediately after sampling and shipped to the lab on ice. Filters were extracted with 10 ml sterile pyrogen-free water by shaking for two hours at room temperature and analyzed for endotoxin using the QCL-1000 assay (Whittaker Bioproducts, Inc., Walkersville, MD). Results are reported in endotoxin units per cubic meter of air (EU/m^3). Reynolds et al. have previously reported a coefficient of variation for this method of 0.17 for total endotoxins.[22]

Total Bioaerosols

Total bioaerosols (culturable and non-culturable) were collected and analyzed on one day at each fixed sample site using a "direct count" method involving staining of the microorganisms with a fluorescent dye, followed by quantitation using flow cytometry as described by Lange et al.[24] Samples were collected on 25 mm polycarbonate nucleopore filters ($0.4 \mu m$ pore size) with vacuum pumps at flow rates of 2.0 Lpm for 8 hours. Airborne concentrations were calculated by dividing total organisms on the filter by the volume of air sampled (org/m^3).

Respirable Particulates (PM10)

Respirable particles (PM10) were collected on one day at the fixed sample sites using a calibrated vacuum pump and impactor (Air Diagnostics Inc., Naples, ME) at a flow rate of 20 Lpm. Particles smaller than 10 μm passed through the impactor and were collected on pre-weighed 37 mm glass fiber filters (Gelman Scientific, St Louis, MO). Filters were pre- and post-weighed using a Mettler Toledo Model MT-5 balance (Hightstown, NJ).

Sound Level

Sound pressure levels were monitored continuously at the fixed sample sites using Quest Q100 Noise Dosimeters (Quest Technologies, Oconomowoc, WI). Shorter-term samples were collected at the mobile sample locations. The dosimeters were set to a range of 40 to 110 dB[A], with a 3 dB doubling rate, and slow response. Data were recorded every minute, and downloaded to a laptop computer using QuestSuite software version 1.0.008C (Quest Technologies, Oconomowoc, WI).

Illuminance

Illuminance (lux) was measured with an Extech Model 407025 Foot Candle/Lux Meters (Extech, Foxboro, MA) using the fluorescent light mode. The mean, maximum, and minimum values were recorded manually at the end of each day.

Study Population, Occupant Perceptions, and Symptoms

Prior to recruitment of subjects, extensive efforts were made in conjunction with supervisors and worker representatives to promote the study. While sample collection proceeded on Monday through Wednesday, supervisors were asked to provide occupants with background information on the study and to encourage them to participate. All occupants of the test spaces who worked more than 20 hours per week were invited to participate. Participants were recruited based on informed consent (University of Iowa Institutional Review Board) and a self-administered questionnaire was distributed on Thursday morning of the monitoring week. Recruitment of subjects continued through Friday morning. Subjects returned questionnaires by dropping them anonymously into a collection box or by mailing them in pre-addressed stamped envelopes. Demographic information was also collected for all occupants of the building to evaluate representativeness of the participants.

Four standardized questionnaires were combined and used to document participant demographics, symptoms, and psychosocial attributes. The New Standard Environmental Inventory Questionnaire for Estimation of Indoor Concentrations (NIOSH/EPA Questionnaire), which EPA used for their BASE studies, was supplemented by the Job Content Questionnaire (JCQ) developed by Karasek et al. to evaluate job satisfaction for the Framingham Study, the Brief Symptom Inventory (BSI), and the Medical Outcomes Short Form Health Survey (MOS).[12,26–28] The questionnaire was peer-reviewed and pilot-tested for content and time needed for completion. The NIOSH/EPA questionnaire has been used by NIOSH recently for Health Hazard Evaluations and was used by EPA as part of their BASE protocol.[12,16] This questionnaire documents demographic information, work-related symptoms, and perceptions of the work environment. A short version of the JCQ (58 questions) focuses on issues related to job satisfaction.[26] The BSI 90-R has been used extensively to measure general psychological well being in a clinical setting and provided information on general psychological symptoms experienced in the past month.[27] The MOS is designed to assess physical and occupational (practical) functioning in addition to

the subject's self-assessment of general health.[28] Results from the JCQ, BSI 90-R, and MOS are presented in scales, which summarize individual items.

Quality Assurance

Quality assurance/quality control included use of laboratory blanks, field blanks, laboratory spikes, field spikes, and duplicate samples for each field trip. Direct reading instruments were calibrated daily in the field using traceable standards, and pumps were calibrated before and after sampling each day. Completeness and accuracy of data entry were also evaluated.

Data Management

Data were compiled in several forms. Several computer files were entered directly in the field for the building systems. Direct reading instrument outputs were downloaded in the field onto a laptop computer from data loggers. Field data were recorded manually from HVAC analysis, logs, and data from laboratory analysis of environmental samples. Occupant questionnaire results were coded, and personal identifiers were removed to maintain confidentiality. Questionnaire data were entered into Epi-Info 6.0 (World Health Organization, Geneva). Environmental and building data were entered either into a database provided by EPA for this study (IADCS) or into Microsoft Excel (Microsoft Corporation, Redmond, WA).

Statistical Analysis

Databases from all sources were combined and analyzed using SAS Version 6.0 (SAS Institute, Cary, NC). Descriptive statistics were used to characterize the distributions of building characteristics, environmental measurements, and questionnaire responses. The normality of data was tested using the W statistic developed by Shapiro and Wilk as computed within SAS UNIVARIATE. In some cases data were log-transformed before proceeding with statistical analysis. Geometric means and geometric standard deviations were calculated for environmental data that could be described using a lognormal model. Comparisons between buildings were made using either analysis of variance, chi square, Wilcoxon rank sum, or Kruskal-Wallis tests, depending on the particular environmental or questionnaire data. Spearman correlation coefficients were calculated to evaluate associations among environmental parameters, and among symptoms and environmental parameters.

RESULTS

Buildings

The six buildings selected for this study were located in Des Moines, Iowa (2); Omaha, Nebraska; and St. Paul, Minneapolis, and Plymouth, Minnesota.

Building #1 is a four-story structure built in 1978 with 15,717 m^2 and 453 total employees. The test space included the top two floors, which were served by central and perimeter

heating, ventilating, and air-conditioning (HVAC) units located in a penthouse operating in a constant air volume (CAV) mode. A total of 210 people occupied the study space of 5,929 m^2. Data were collected in November 1996.

Building #2 is an older 15-story structure built in 1965, with a total workforce of 800 occupying 21,422 m^2. Fifty-five employees worked in the test space, on the fourth floor (1,366 m^2). This area was served by two air handlers, one drawing air from a central shaft and one drawing air directly from outside the fourth floor. Both were operated in a variable air volume (VAV) mode. Data were collected in December 1996.

Building #3 is a 17-story tower built in 1981, with 1,410 workers occupying 42,732 m^2 total area. The test space included the eighth, ninth, and thirteenth floors which were served by two air-handling units located in a penthouse on the roof and operating in VAV mode. A total of 201 employees were stationed in the test space which occupied 6,133 m^2. Data were collected in January 1997.

Building #4 is a 14-story structure consisting of three co-terminus buildings erected in 1937, 1967, and 1977. A total of 1,047 employees worked in the 41,805 m^2 total space of this building. The test space was limited to the eighth floor (2,152 m^2), which was occupied by 78 individuals. The test space was served by two air-handling units, one located in a penthouse, the other located on the 8th floor and drawing air from a shaft, both operating in the VAV mode. Data were collected in February 1997.

Building #5 is a 10-story structure built in 1913, with a total workforce of 774 occupying 28,051 m^2. The study zone included the fifth and seventh floors, which shared two air-handling systems located in a penthouse and providing central (VAV) and perimeter ventilation (CAV). Seventy-eight employees occupied the 2,806 m^2 of the study area. Data were collected in March 1997.

Building #6 is a four-story structure built in 1972, with 567 workers in a total space of 19,654 m^2. The test space consisted of one half of the second floor, served by an air handler (VAV) located in the basement and drawing outside air from a shaft extending to the top of the building. Sixty-six employees worked in the 3,252 m^2 of the study zone. Data were collected in April 1997.

Buildings #1 through #5 were all located in downtown urban areas, and building #6 was located in a suburban area next to a major highway. The arrangement of the study spaces in all six buildings consisted of open, carpeted areas with individual fabric-covered systems furniture. Most occupants of all six buildings performed comparable tasks, with heavy use of personal computers to monitor operations and provide customer service.

Ventilation

Table I summarizes results of ventilation measurements made during the first visit to these six buildings (November 1996 to April 1997). Volumetric air flows were measured in supply ducts

TABLE I
Volumetric air flow, calculated recirculation, and CFM outdoor air supplied per person[A]

	Building					
	1	2	3	4	5	6
Outdoor CO_2 (ppm)	385	394	461	254	389	361
Return CO_2 (ppm)	636	525	579	495	508	459
Supply CO_2 (ppm)	590	440	551	447	468	406
Percent recirculation	19.9	82.4	50.6	19.4	34.4	54.8
Air flow rate (cfm)	9090	1900	8470	920	9280	2810
# People	210	55	201	78	78	66
CFM/person	35	10	22	13	79	19

[A]N = 6 in each cell for all samples.

of the air-handling systems providing central ventilation to the test spaces, once in the morning and once in the afternoon on Wednesday and Thursday of the site visit. Carbon dioxide was also measured at the same times in the outdoor, supply, and return air. The results are therefore arithmetic averages of multiple samples. In all cases, outdoor carbon dioxide concentrations are lower than supply concentrations, with return air concentrations the highest. Supply air concentrations of CO_2 ranged from 406 ppm to 590 ppm. The percent recirculated air was calculated based on these measurements using the EPA's IAQ database ventilation module. The proportion of recirculated air varied from a low of 19 percent in buildings #1 and #4 to 82 percent in building #2. The volumetric air flow rates also varied by building, ranging from a low of 920 cfm in building #4 to 9280 cfm in building #5. Accounting for recirculation, the rate of outdoor air supplied per person in these buildings varied from 10 cfm/person in building #2 to 79 cfm/person in building #5.

TABLE II
Gases and comfort parameters—Q-Trak measurements[A]

	Geometric mean (GSD)			
Building	CO_2 (ppm)	CO (ppm)	Temp. (°C)	Relative humidity (%)
1	593 (1.1)	1.0 (1.1)	24.8 (1.0)	21 (1.1)
2	520 (1.5)	1.2 (1.5)	24.2 (1.0)	23 (1.1)
3	573 (2.4)	1.5 (2.4)	24.0 (1.0)	13 (1.1)
4	505 (1.1)	1.0 (1.1)	23.6 (1.8)	24 (1.3)
5	518 (1.0)	1.0 (1.0)	24.6 (1.0)	22 (1.1)
6	388 (1.0)	1.0 (1.0)	22.8 (1.0)	12 (1.3)
Kruskal-Wallis[B] p =	<0.01	<0.01	<0.01	<0.01

[A]N = 12 in each cell for all samples. Duplicates at one location were averaged before averaging over multiple locations.

[B]While the tables present means by buildings, the Kruskal-Wallis tests are based on multiple readings within each building.

Environmental Parameters

Table II presents a summary of comfort parameters measured continuously at the three fixed locations in each building. The geometric mean and geometric standard deviations for carbon dioxide, carbon monoxide, temperature, and relative humidity determined using Q-Traks are presented. In each case, the parameters differed significantly among buildings (p < 0.01). Measures of carbon dioxide, carbon monoxide, and temperature were within ranges anticipated for nonproblem buildings. Relative humidity was low in all buildings ranging from 12 percent in building #6 to 24 percent in building #4. Geometric standard deviations indicate little variability between sample stations for these parameters, except for CO_2 and CO in building #3.

Results for total volatile organic compounds (TVOCs), formaldehyde, and acetaldehyde are presented in Table III. All samples were collected over one day at three sampling stations in each building study area. TVOCs, quantified as toluene, ranged from 73 $\mu g/m^3$ to 235 $\mu g/m^3$. A large variety of individual VOCs were identified with as many as 40 different compounds at some sampling locations. The most prevalent compounds (in

TABLE III
Total volatile organic compounds (TVOCs) and aldehydes $(\mu g/m^3)$[A]

	Geometric mean (GSD)		
Building	TVOC	Formaldehyde	Acetaldehyde
1	104 (1.1)	5.0 (1.2)	<3.0
2	145 (3.4)	13.3 (1.3)	7.5 (1.3)
3	73 (1.7)	11.7 (1.8)	5.8 (1.1)
4	117 (1.1)	1.7 (1.2)	<3.0
5	235 (2.4)	8.1 (1.5)	5.1 (1.6)
6	114 (1.1)	5.4 (1.1)	<3.0
Kruskal-Wallis p =	0.05	<0.01	<0.01

[A]N = 4 in each cell for all samples. Duplicates at one location were averaged before averaging over multiple locations.

TABLE IV
Most prevalent VOCs by building (mean indoor concentrations)

Building	Rank order of prevalence		
	First	Second	Third
1	Toluene (3.7 μg/m^3)	Limonene (3.0 μg/m^3)	Xylene (2.7 μg/m^3)
2	Xylene (3.9 μg/m^3)	Heptane (2.6 μg/m^3)	2-Propanol (2.6 μg.m^3)
3	Xylene (3.8 μg/m^3)	Toluene (2.7 μg/m^3)	2-Propanol (2.5 μg/m^3)
4	2-Propanol (7.7 μg/m^3)	Heptene (3.2 μg/m^3)	Toluene (2.9 μg/m^3)
5	2-Propanol (7.9 μg/m^3)	Toluene (4.7 μg/m^3)	Xylene (3.2 μg/m^3)
6	Limonene (1.8 μg/m^3)	Xylene (1.6 μg/m^3)	Toluene (1.5 μg/m^3)

rank order) and the mean indoor concentrations found by building are presented in Table IV. The most commonly detected compounds included heptane, heptene, limonene, 2-propanol, toluene, and xylene. Especially in buildings #2 and #5, TVOC concentrations varied more among sampling locations (had a larger geometric standard deviation) than carbon dioxide and carbon monoxide. Mean indoor formaldehyde concentrations ranged from 5.0 to 13.3 μg/m^3, and mean indoor acetaldehyde concentrations ranged from <3.0 to 7.5 μg/m^3. Outdoor concentrations of TVOCs and aldehydes were consistently lower than indoor concentrations.

Airborne concentrations of culturable bacteria and fungi at both indoor and outdoor locations were low, with few samples exceeding 100 CFU/m^3 (Tables V and VI). Airborne concentrations of thermophilic bacteria were consistently lower than mesophilic bacteria levels. There were no statistical differences between morning and afternoon samples. Indoor concentrations of mesophilic and thermophilic bacteria were lower than outdoor concentrations in buildings #1, #2, and #3, but higher in buildings #4, #5, and #6. The only building in which this difference may be significant is building #6, where mesophilic bacteria were

148 CFU/m^3 indoors and 48 CFU/m^3 outdoors. Outdoor fungal concentrations consistently exceeded indoor concentrations except for buildings #5 and #6. Again the differences are not significant. In most cases the predominant genera detected were *Cladosporium* and *Penicillium*. There was greater variability among sample locations for culturable bacteria than for gases and vapors, with geometric standard deviations of up to 3.3.

Respirable particulates (PM10) were generally low, ranging from below limits of detection (0.1 μg/m^3) in building #2 to 36 μg/m^3 in building #3 (Table VII). Concentrations of PM10 particles were uniformly distributed between sample locations within buildings. Outdoor concentrations were similar to indoor concentrations. Endotoxin concentrations in commercial buildings have not been previously reported, but were far lower than levels typical of environments with organic dusts. Geometric mean concentrations ranged from 0.5 EU/m^3 in building #2, to 3.0 EU/m^3 in building #5 (Table VII). Endotoxin concentrations within buildings were variable, with geometric standard deviations up to 2.7 in building #3. Airborne endotoxin levels differed statistically between buildings. Total bioaerosols, measured using a fluorescent staining technique, have also not been

TABLE V
Culturable bacteria (CFU/m^3)[A]

Building	Geometric mean (GSD for indoor locations)			
	Mesophilic bacteria		Thermophilic bacteria	
	Indoor	Outdoor	Indoor	Outdoor
1	83 (1.6)	110	27 (3.3)	58
2	100 (2.3)	116	12 (2.1)	20
3	34 (2.3)	100	7 (0)	35
4	41 (1.6)	17	ND	ND
5	46 (2.2)	43	18 (0)	7
6	140 (1.7)	48	18 (0)	ND
Kruskal-Wallis p =	<0.01		0.83	

[A]N = 16 in each cell for all indoor samples. N = 4 in each cell for outdoor samples. Duplicates at one location were averaged before averaging over multiple locations. Bacterial genera were not identified.

ND = None detected.

TABLE VI
Culturable fungi (CFU/m^3)[A]

	Geometric mean (GSD for indoor locations)				
	Fungi			Fungi	
Building	Indoor	Predominant genera	Outdoor	Predominant genera	
1	83 (1.6)	*Cladosporium spp.* *Penicillium spp.*	525	*Cladosporium spp.* *Penicillium spp.*	
2	100 (2.2)	*Cladosporium spp.* *Penicillium spp.*	165	*Cladosporium spp.* *Penicillium spp.*	
3	14 (1.8)	*Cladosporium spp.* *Penicillium spp.*	67	*Cladosporium spp.* *Penicillium spp.*	
4	14 (2.0)	*Cladosporium spp.* *Penicillium spp.*	17	*Cladosporium spp.* *Penicillium spp.*	
5	29 (3.0)	*Cladosporium spp.* *Penicillium spp.* *Aspergillus niger*	25	*Aspergillus spp.*	
6	20 (1.8)	*Cladosporium spp.* *Aureobasidium spp.* *Verticillium spp.*	31	*Cladosporium spp.* *Paecilomyces spp.* *Nocardia spp.*	
Kruskal-Wallis p =	<0.01				

[A]N = 16 in each cell for all indoor samples. N = 4 in each cell for outdoor samples. Duplicates at each location were averaged before averaging over multiple locations.
ND = None detected.

reported previously for commercial buildings. Concentrations of total bioaerosols ranged from 510 organisms/m^3 in building #4, to 10,700 organisms/m^3 in building #2 (Table VII). Concentrations in building #1 were too high to enumerate. Total bioaerosol concentrations were quite variable within buildings. Geometric standard deviations were as high as 10.8 in building #2. There were no statistically significant differences among buildings.

Results of noise and light measurements are presented in Table VIII. Geometric mean noise levels ranged from 48 dB[A] in building #3 to 56 dB[A] in building #4. Noise levels were quite uniform within buildings. Light measurements ranged from 200 lux in building #1 to 420 lux in building #2, and were also fairly uniformly distributed within buildings.

Environmental Correlations

Significant (p <0.10) Spearman rank correlations among environmental parameters are presented in Table IX. Carbon dioxide, which is often interpreted as an indicator of ventilation, was positively correlated with formaldehyde (r = 0.63), acetaldehyde (r = 0.65), culturable fungi (r = 0.42), and total

TABLE VII
Particulates—PM10, endotoxin, and total bioaerosols[A]

	Geometric mean (GSD)		
Building	PM10 (μg/m^3)	Endotoxin (EU/m^3)	Total bioaerosols (organisms/m^3)
1	25 (1.0)	0.9 (1.4)	Not quantifiable[B]
2	<0.1 (0)	0.5 (1.4)	10,700 (10.8)
3	36 (1.0)	0.7 (2.7)	8,850 (2.6)
4	20 (1.0)	1.3 (1.3)	509 (3.5)
5	16 (1.0)	3.0 (1.9)	1,520 (1.5)
6	14 (1.0)	1.4 (1.1)	1,370 (1.0)
Kruskal-Wallis p =	0.04	<0.01	0.27

[A]N = 4 in each cell for all samples. Duplicates at one location were averaged before averaging over multiple locations.
[B]Too high to enumerate.

TABLE VIII
Noise (dBA) and Light (Lux)[A]

	Geometric mean (GSD)	
Building	Noise	Light
1	51 (1.1)	200 (1.0)
2	55 (1.1)	420 (1.1)
3	48 (1.0)	400 (1.2)
4	56 (1.0)	260 (1.2)
5	50 (1.1)	380 (2.2)
6	52 (1.1)	410 (1.1)
Kruskal-Wallis p =	0.10	<0.01

[A]N = 4 in each cell for all samples. Duplicates at one location were averaged before averaging over multiple locations.

TABLE IX
Significant Spearman rank correlations among environmental parameters (n = 18)

Parameters	r	p
CO_2–TVOC	−0.49	0.06
CO_2–Formaldehyde	0.63	0.01
CO_2–Acetaldehyde	0.65	0.03
CO_2–Total bioaerosol	0.52	0.05
CO_2–Fungi	0.42	0.09
CO–PM10	0.81	<0.01
CO–Endotoxin	−0.64	0.01
Temp.–Formaldehyde	0.46	0.07
Temp.–Fungi	0.44	0.08
Temp.–Thermophilic bacteria	0.63	0.09
RH–TVOC	0.48	0.07
TVOC–Endotoxin	0.51	0.05
Formaldehyde–Acetaldehyde	0.85	<0.01
Formaldehyde–Total bioaerosol	0.55	0.08
Fungi–Mesophilic bacteria	0.52	0.03

TABLE X
Means by gender of NIOSH/EPA questionnaire parameters

Parameters	Men	Women	p value[A]
N	86	282	
Age	46.2	45.9	0.61
Years in job title	8.1	7.6	0.68
Years in building	4.2	5.7	<0.01
No. work-related symptoms	3.0	4.4	0.01
Authority conflict	1.7	1.6	0.31
Stress	3.0	3.0	0.44
Self-report of exposure	3.1	3.1	0.87
Overall job satisfaction	2.1	2.0	0.24
Job category	—	—	0.06

[A]Comparison of means using t-test with unequal variance.
Five individuals did not report gender and are not included in results that stratify by gender. Scale ranges from 1 to 4 for authority conflict; 1 to 5 for stress, self-report of exposure, and job satisfaction.

Symptoms and Psychosocial Characteristics

Demographic characteristics of participants completing questionnaires are presented in Table X. Male and female participants both averaged about 46 years of age and had worked in the same job for about 8 years. The only significant differences between males and females was the length of time in the study buildings—males averaged 4.2 years and females 5.7 years—and the number of work-related symptoms reported. Females reported an average of 4.4 work-related symptoms, while males reported 3.0.

Tables XI and XII summarize specific work-related symptoms by building, ascertained using the NIOSH/EPA

bioaerosols (r = 0.52). Carbon dioxide was negatively correlated with TVOCs (r = −0.49). Temperature was positively correlated with formaldehyde (r = 0.46), culturable fungi (r = 0.44), and thermophilic bacteria (r = 0.63). TVOCs were positively correlated with relative humidity (r = 0.48) and endotoxins (r = 0.51). Formaldehyde and acetaldehyde were strongly correlated (r = 0.85). Fungi and mesophilic bacteria were positively correlated (r = 0.52). Endotoxin and total bacteria were not correlated with each other, or with culturable bacteria (p > 0.10).

TABLE XI
Percentage of participants reporting respiratory symptoms

				Building					
		1	2	3	4	5	6	Overall	
Symptoms	n =	91	30	100	48	51	53	373	p value[A]
Dry, itching, or irritated eyes		52	50	33	50	39	24	41	<0.01
Tired or strained eyes		48	47	31	60	41	34	42	0.01
Cough		16	17	11	10	12	9	13	0.75
Sore or dry throat		3	23	16	23	18	25	22	0.30
Sneezing		27	50	21	25	24	19	25	0.03
Stuffy/runny nose or sinus congestion		35	37	18	21	24	17	25	0.03
Fatigue or drowsiness		33	40	15	33	29	22	27	0.02
Shortness of breath		5	7	2	9	4	4	5	0.60
Wheezing		3	7	2	9	10	2	4	0.40
Chest tightness		7	13	2	9	10	2	6	0.09

[A]Kruskal-Wallis Chi Square.

TABLE XII
Percentage of participants reporting CNS, dermal, and musculoskeletal symptoms

Symptoms	Building						Overall	p value[A]
	1	2	3	4	5	6		
Headache	48	47	30	50	43	28	40	0.04
Feeling depressed	14	20	15	10	10	16	14	0.80
Tension, irritability, or nervousness	42	53	29	46	33	37	37	0.04
Difficulty remembering or concentrating	13	13	12	25	18	9	14	0.23
Dizziness	15	10	5	13	6	4	9	0.08
Difficulty sleeping	8	17	13	15	14	6	11	0.44
Nausea or upset stomach	13	13	5	9	10	4	9	0.25
Pain/stiffness in back, shoulders, or neck	46	43	37	33	27	32	37	0.25
Numbness in hands/wrists	16	10	13	17	8	9	13	0.69
Dry or itchy skin	17	20	10	9	12	13	13	0.45

[A]Kruskal-Wallis chi-square.

questionnaire. Upper respiratory symptoms, such as dry eyes, tired eyes, stuffy or runny nose, and fatigue were prevalent in a large proportion of the population in all six buildings (Table XI). There were differences in upper respiratory symptoms by building for all symptoms, except cough and sore/dry throat. Lower respiratory symptoms were reported by only a small proportion of participants (Table XI). Participants also reported a high prevalence of central nervous system symptoms (head, tension/irritability) and musculoskeletal symptoms (pain/stiffness in back/shoulders/neck) (Table XII). There were no significant differences between buildings, except for headache and tension/irritability.

Results from the Job Content Questionnaire indicated that, overall, participants ranked their decision latitude, perception of skill discretion, psychological job demands, and decision authority at the mid-ranges of the respective scales. As a group they reported a low sense of job security and the perception that they were exposed to hazardous conditions and toxic exposures. Compared to other populations' responses to the BSI 90-R,[27] this workforce reports a relatively high level of obsessive-compulsive behavior, paranoid ideation, interpersonal sensitivity, depression, somatization, anxiety, and hostility characteristics. While participants perceived themselves as functioning well in their social work environment, they perceived their well-being to be lower, with especially low rankings on the body pain scale.

Symptoms and Environmental Exposures

Relationships between environmental exposures and symptoms were evaluated separately for males and females, by dividing participants into high and low exposure and symptom groups (using a median split) and calculating Kruskal-Wallis chi-square approximations (Table XIII). Significant relations between a high number of symptoms and exposure to environmental parameters including temperature, carbon monoxide, noise, aldehydes, endotoxin, and particulates were found for males. Elevated number of symptoms was only associated with two environmental parameters for females—relative humidity and endotoxin. It is of interest that endotoxin is the only environmental parameter associated with high symptoms in both males and females, although this is of borderline statistical significance.

TABLE XIII
Kruskal-Wallis chi-square approximations for number of symptoms and environmental parameters (n = 6)

Parameters	Men		Women	
	χ^2	p	χ^2	p
Carbon dioxide	0.92	0.34	1.77	0.18
Temperature	**4.68**	**0.03**	0.37	0.54
Relative humidity	1.27	0.26	**3.46**	**0.06**
Carbon monoxide	**3.20**	**0.07**	0.00	0.94
Noise	**4.05**	**0.04**	1.29	0.26
VOCs	0.39	0.54	0.05	0.82
Formaldehyde	**3.40**	**0.06**	0.12	0.73
Acetaldehyde	**3.44**	**0.06**	0.02	0.90
Fungi	1.46	0.22	0.23	0.63
Mesophilic bacteria	0.04	0.83	0.06	0.80
Thermophilic bacteria	1.46	0.23	0.23	0.63
Endotoxin	**3.13**	**0.08**	**2.93**	**0.09**
PM10	**3.69**	**0.05**	0.04	0.84

TABLE XIV

Spearman rank sum correlations of MOS short form scales versus number of symptoms

	Men		Women	
	r	p	r	p
Physical functioning	−0.07	0.52	**−0.17**	**0.00**
Role functioning	−0.03	0.77	**−0.11**	**0.07**
Social functioning	−0.12	0.29	**−0.14**	**0.02**
Body pain	−0.00	0.98	**−0.16**	**0.00**
Mental health	−0.09	0.44	**−0.15**	**0.01**
Health perception	0.07	0.55	**−0.19**	**0.00**

Conversely, there was a strong association between increased number of symptoms and lower scores on psychosocial scales from the MOS short form for females, but not for males (Table XIV).

DISCUSSION

The low levels of most environmental parameters are not surprising, since the buildings selected for this study were defined to be nonproblem buildings. Although carbon dioxide concentrations tended to rise during the workday, they did not approach the commonly recommended threshold of 1,000 ppm.[29] Carbon dioxide concentrations exceeding 1,000 ppm and interpreted as an indicator of insufficient outside air supply have been reportedly associated with increased incidence of SBS in a number of studies.[29] Accounting for recirculation, the rate of outdoor supply air in these buildings ranged from about 10 cfm/person in building #2 to 79 cfm/person in building #5. ASHRAE's current proposed recommendation of 20 cfm/person for general office commercial spaces is met in buildings #1, #3, and #5, with building #6 close to this rate and buildings #2 and #4 clearly deficient.[29] Although temperatures in the study spaces were within the range of 20°C to 26°C recommended for thermal comfort, relative humidity was low in all buildings, especially buildings #3 and #6.[30] Dry air conditions are not uncommon in this region during the heating season, when this first round of sampling was conducted.

Based on studies of problem buildings and human experiments, it has been suggested that levels of VOCs near 160 to 300 μg/m^3 may be associated with symptoms of SBS.[29,31,32] Although generally low, the concentrations of VOCs measured in several of the study buildings approached this range. Concentrations of formaldehyde and acetaldehyde were generally very low (<12 μg/m^3) compared to recommended target concentrations of 120 μg/m^3.[29] Respirable particulate (PM10) concentrations did not exceed the EPA's ambient air quality standard of 50 μg/m^3.[33] Airborne levels of culturable bacteria and fungi were also very low compared to problem buildings, and did not approach the levels of 500 to 1,000 cfu/m^3 previously suggested as guidelines by the ACGIH Bioaerosol Committee and

other researchers.[4,5,11,25,34–36] The ACGIH Bioaerosols Committee has recently moved away from suggesting specific numeric guidelines, and has placed more emphasis on comparison of outdoor and indoor concentrations and genera.

Endotoxin concentrations were far below the levels of about 50 to 90 EU/m^3 thought to be associated with human respiratory disease, based on studies of environments with organic dusts.[37,38] Although no health guidelines have been suggested, total bioaerosol concentrations were also generally orders of magnitude lower than levels measured in agricultural and industrial environments.

It has been suggested that noise levels near 55 dBA may interfere with speech communication, and also therefore contribute to increased stress and annoyance.[39,40] Noise levels in these buildings approached or exceeded this level. The level of lighting was quite variable among buildings, and there is evidence that inadequate lighting may contribute to fatigue, irritability, and decreased efficiency.[41,42] The levels measured in these buildings are within ranges reported by other researchers.[41–43]

The greater variability among sample locations for total bioaerosols, endotoxins, and organic compounds compared to the low spatial variability for comfort parameters, including carbon dioxide, suggests that sampling and control strategies need to account for potential microclimate sources and differences in the factors affecting dispersion of these parameters. The strong correlations between many of these environmental parameters also should be considered in designing sampling and control strategies. The consistent correlation between carbon dioxide and other environmental parameters reinforces the importance of ventilation as a control. The negative relationship between carbon dioxide and TVOCs is, however, unexpected and needs to be further explored in the full data set for these buildings.

Compared to other studies of nonproblem buildings where similar questionnaires were used, this population reported an elevated incidence of upper respiratory, central nervous system, and musculoskeletal symptoms.[12–15] The increase in upper respiratory system complaints may be due to the effect of season, since these data were collected during the dry and cold winter months. Some symptoms may also be related to the extensive reorganization and downsizing experienced by this workforce several months before data collection was initiated. The elevated rates of anxiety, stress, and low perception of job security could also be explained by this situation. The relatively high proportion of workers reporting symptoms suggestive of emotional distress (e.g., elevated BSI subscales) might be indicative of a selection process in the recruitment and hiring of workers for this service sector industry.

The gender differences in associations among symptoms, environmental exposures, and psychosocial factors confirm the importance of addressing psychosocial interventions as part of a comprehensive prevention and response strategy. The higher proportion of females reporting work-related symptoms is consistent with empirical observations reported for cases of SBS.

There is, however, little practical difference between the average number of symptoms reported by males and females in this study. It is noteworthy that endotoxin was the only environmental factor associated with increased symptoms in both males and females. A number of studies have demonstrated the relationship between high endotoxin exposure and respiratory dysfunction in agricultural settings, and the biological basis for this effect is well understood. Effects from low-level exposures have not been previously documented. This relationship is suggestive and needs to be further explored in the full data set. The difference between males and females in the relation of symptoms to psychosocial parameters is perhaps not unexpected, given cultural differences in male and female behavior relative to "stoicism" and other patterns of gender-specific behavior. This difference is important and needs to be considered when designing management strategies to prevent and respond to IEQ problems.

CONCLUSIONS

Unique aspects of this study included the measurement of endotoxin, total bioaerosols, and in-depth evaluation of psychosocial parameters in relation to indoor environmental quality in commercial office buildings. In the first round of sampling, conducted during the heating season, airborne concentrations of chemicals and microbial organisms were generally low compared to problem buildings. Upper respiratory symptoms, headache, and backaches were elevated, and psychosocial characteristics including obsessive-compulsive behavior, psychotism, somatization, and anxiety were also elevated. Importantly, psychosocial factors were significantly related to increased numbers of symptoms in females, while environmental factors were correlated with symptoms in males. The association between low airborne endotoxins and symptoms in this environment is a new finding. The results of this study will add data on buildings from the midwestern region of the United States to the EPA national IEQ database. These data will be useful in generating hypotheses for further studies of IEQ, and will also help to identify and to quantify the factors that contribute to sick building syndrome. The data will also be used to evaluate the effectiveness of current building operation practices, and can be used to prioritize allocations of resources for reduction of risk associated with IEQ complaints.

ACKNOWLEDGMENTS

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